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**Kierat, W.; Bolashikov, Zhecho Dimitrov; Melikov, Arsen Krikor; Popioek, Z.; Brand, Marek**

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# Exposure to coughed airborne pathogens in a double bed hospital patient room with overhead mixing ventilation: impact of posture of coughing patient and location of doctor

## ABSTRACT

*The exposure of a doctor and a patient to air coughed by a second infected patient was studied in a mock-up of two-bed hospital infectious ward with mixing ventilation at 22°C (71.6 F) room air temperature. The effect of posture of the coughing patient (lying sideways or on back), position of the doctor (either facing the coughing patient or standing sideways) at three ventilation rates (3 h<sup>-1</sup>, 6 h<sup>-1</sup> and 12 h<sup>-1</sup>) was examined. Thermal manikin with realistic body shape and surface temperature distribution was used to resemble the doctor. The coughing patient was simulated by a heated dummy with a cough generator. Another heated dummy was used to simulate the second patient in the second bed. The cough consisted of 100% CO<sub>2</sub>. The Peak Cough Time was 4 s, when the doctor was close to coughing patient and increased more than twice for the exposed patient. The level of exposure (Peak Concentration Level) depends on the positioning relative to the cough direction: lying or standing still, facing or turned sideways and changed varied 194 to 10228 ppm. Ventilation rates of 12 h<sup>-1</sup> (recommended by present hospital standards) resulted in increased background exposure levels and may suggest risk from airborne cross-infection.*

## INTRODUCTION:

With the emergence of new and the mutation of well-known pathogens causatives of epidemics and pandemics the hospitals become in the front line of the attempt to control and stop the disease spread. Pathogens may be present in the air exhaled by an infected person. Ventilation becomes one of the major methods used nowadays for reduction and control the spread of pathogens via the airborne route in hospital premises, the (Streifel 1999, Kaushal et al. 2004, Beggs et al. 2008).

Ventilation rates of minimum 12 h<sup>-1</sup> (air change per hour – ACH) is recommended in the present guidelines and standards for hospital insulation rooms (ASHRAE 170 2008, CDC guidelines 2005, etc.). Several factors, such as air change rate (Kao and Yang 2006) and air distribution pattern (Qian et al. 2006, Noakes et al. 2009,

Tung et al. 2009) affect the dispersion of airborne contaminants and thus have an impact on the risk from airborne cross infections in hospital premises. The distance between the sick patient (source of pathogens) and the medical staff member (doctor/nurse), as well as the mechanism of atomization of airborne particles (through speaking, breathing or coughing) are some of the other factors affecting the airborne cross-infection in hospitals. Under certain conditions (room layout, positioning of doctor and infected patient, etc.) these may even be more important than the ventilation rate itself. The interaction of coughed flow with high initial velocity ranging from 6 m/s (1181.1 fpm) up to 30 m/s (5905.51 fpm) (Edwards et al. 2004, Zhu et al. 2005, Sun and Ji 2007, Gupta et al. 2009) with the free convection flow around human body and the ventilation flow will be different than the flow of exhalation with much low initial velocity (Gupta et al. 2010). Hence the strategy of supplying extra amounts of outdoor air aiming to dilute the polluted room air may not be effective in protecting from airborne cross-infection due to coughing. The exposure of medical staff and patients in a hospital room to air coughed by an infected patient has not been studied in deep.

The exposure of a doctor and a patient to the air coughed by a second infected patient was studied in a mock-up of two-bed hospital infectious ward with mixing ventilation. The effect of the posture of the coughing patient, the positioning of the doctor relative to the source patient (coughing individual) and the level of the ventilation rate on the exposure is within the focus of the present study. The effect of the distance between the doctor and the infected coughing patient on the airborne cross-infection in a hospital infectious ward is reported by Bolashikov et al. (2010).

## **METHOD**

Experiments were designed and performed in a full-scale experimental room with dimensions 4.65 m x 4.65 m x 2.60 m (15.26 ft x 15.26 ft x 8.53 ft) (W x L x H) furnished to simulate a hospital isolation room with two beds. The distance between the beds was set at 1.3 m (4.27 ft). Five ceiling-mounted light fixtures (6 W (20.47 Btu/h) each) provided the background lighting. The room was located in a tall hall, where the temperature was kept constant and equal to the air temperature in the test room. A heated dummy with simplified body geometry, equipped with a coughing machine was used to simulate the coughing sick patient lying in one of the beds. The mouth of the coughing patient was simulated as a circular opening (diameter of 0.021 m (0.069 ft)). The characteristics of the cough were: volume peak flow - 10 L/s (21.19 cfm) volume of the cough - 2.5 L (11.33 ft<sup>3</sup>) cough time interval - 0.5 s, maximum cough velocity - 28.9 m/s (5688.98 fpm). A second heated dummy was used to simulate a patient lying in a bed aligned with the bed of the coughing patient. A dressed

thermal manikin (1.02 Clo) with realistic human body size, shape and surface temperature distribution was used to resemble a “doctor”. The layout of the set-up is shown in Figure 1.

Mixing type of air distribution was used to condition the air in the room. The air supply diffuser (a four way diffuser) and two air exhausts (a perforated square diffusers mounted above the heads of the patients) were installed on the ceiling. The exhaust air was equally balanced between the two outlets. The supplied air was 100% outdoor (no recirculation was used). A slight under-pressure of  $1.6 \pm 0.2$  Pa ( $0.48 \pm 0.06$  in. of Hg) was kept during all the experiments in order to avoid leaking of air from the test room to the tall hall. The supply air temperature and the supplied and exhaust air flow rate were continuously controlled to keep the set values defined for each of the tested conditions.

Experiments were performed at three air-change rates (ACH): 3, 6 and  $12 \text{ h}^{-1}$ . Room temperature was kept at  $22^\circ\text{C}$  (71.6 F). The relative humidity was not controlled but was measured to be between 35% and 45% during the experiments. The coughing patient was either lying on one side and was facing the doctor or on the back with face turned upwards towards the ceiling (Figure 1b). Measurements were performed when the doctor was standing between the two beds and facing the coughing patient from a distance of 0.55 m (1.8 ft) (Figure 1b) and when the doctor was standing sideways between the two beds and facing the two patients.(Figure 1c). The coughed flow was 100%  $\text{CO}_2$ . The time dependent  $\text{CO}_2$  concentration was measured at the mouth of the doctor with specially developed instrument (PS331) with time constant of 0.8 s and a sampling rate of 4 Hz. The sampling tube of the PS331 was placed at the mouth 0.005 m (0.016 ft) away from the lips and the breathing function of the heated manikin was switched off. As reported in the literature the  $\text{CO}_2$  concentration measured in this way is equal to the  $\text{CO}_2$  concentration in the air inhaled by breathing thermal manikin (Melikov and Kaczmarczyk 2007, Rim and Novoselac 2009). The acquired data were analyzed by specially developed software. The software used second order polynomial extrapolation to get the initial value of the  $\text{CO}_2$  concentration up to 14 000 ppm by applying calibration equations. Frequency correction of the signal from the instrument and compensation for the time needed for the  $\text{CO}_2$  sample to travel from the measuring point to the instrument was applied. Four Indoor Air Quality Monitors (IAQM) PS32, with recording frequency of 0.1 Hz and resolution of 1 ppm, were used to measure the  $\text{CO}_2$  concentration at the mouth of the doctor (position 2, Figure 1), at the air supply diffuser (position 4, Figure 1), at the exhaust diffuser (position 5 above the coughing patient (1), Figure 1), as well as in a point in the room located at 1.7 m (5.58 ft) above the floor close to bed of the infected patient (Point A, Figure 1). For each of the studied 9 conditions (three ventilation rates and three distances between the coughing patient and the doctor) 15 to 20 repeated measurements of simulated cough were

collected and averaged. Only one cough at the time was generated. Each of the repeated coughs was generated after the background CO<sub>2</sub> level reached the level before the cough. The time between the produced repeated coughs decreased with the increase of the background ventilation rate. The excess concentration of CO<sub>2</sub> over the background level was used as criteria for exposure assessment.

Two more parameters were analyzed, namely the Peak Concentration Level (PCL) and the Peak Concentration Time (PCT). PCL is defined as the maximum concentration measured at the mouth of the doctor after a cough is generated; PCT is defined as the time at which the PCL is reached after a cough is generated (Melikov et al. 2009).

## RESULTS AND DISCUSSION

### Exposure of the doctor to coughed air

The effect of different background ventilation rate (3, 6 and 12 h<sup>-1</sup>) on the transport of the air coughed by the sick patient to the mouth of the “doctor” is shown in Figure 2. The figure compares the excess CO<sub>2</sub> concentration measured in time at the mouth of the “standing doctor” (a thermal manikin) situated 0.55 m (1.8 ft) from the mouth opening of the dummy generating the cough. The measurements when the coughing dummy was placed lying on one side with mouth opening directed towards the front body plane of the doctor are shown in Figure 2a and when the coughing dummy was lying on the back and coughing towards the ceiling are shown in Figure 2b. The results in Figure 2a show that when a cough was triggered the “puffed” air first hit the doctor in the abdominal area and then spread over the body; some of the coughed air would glide along the waist of the standing doctor and some would spread upwards (towards the mouth) and downwards (towards the feet). At this position of the “doctor” the PCT values almost did not depend on the air change rate, due to the high initial momentum of the single coughed air. Around the 4<sup>th</sup> second after the cough the puffed CO<sub>2</sub> cloud reached the breathing zone of the thermal manikin followed by decay in concentration. The PCL and the slope of the decay depend on the air change rate in the room: the higher the ventilation rate, the lower the PCL measured and the steeper the slope (faster decay). The values of PCL for 3 and 6 h<sup>-1</sup> were similar: 10228 ppm and 10197 ppm. This might be explained with the fact that the restored after the cough convective layer around the manikin (Bolashikov et al. 2010) entrained and brought into the breathing zone of the manikin room air that was already mixed with coughed air. The lowest PCL of 6847 ppm was for 12 h<sup>-1</sup>.

Figure 2b shows the exposure of the doctor under the same other condition as in Figure 2a but when the infected patient was lying on the back and was coughing upwards. In this case the PCL is much lower (over 50 times) than in the case when cough was made in horizontal direction, suggesting that the largest portion of the

released by the infected patient pathogen laden air through coughing would move upwards due to the high initial momentum. The increase in the ventilation rate decreased the exposure to coughed air similarly to the case when coughing sideways. The highest PCL (200 ppm) measured around the 36<sup>th</sup> second at 3 h<sup>-1</sup> is due to the fact that the existing convective flow around the doctor's body has entrained and moved upward toward the mouth the surrounding room air contaminated after the cough. At this air change rate the background air velocities (lower than 0.1 m/s (19.69 fpm)) were not high enough to disturb or destroy the boundary layer (Bolashikov et al. 2010). For 6 and 12 h<sup>-1</sup> no clear trend for PCT or PCL could be noticed due to the small fluctuations in the excess CO<sub>2</sub> measured as a result from the air flow interaction in the room. The total volume ventilation did not have as significant impact on the exposure level as in the studied case when the patient coughed sideways towards the face of the doctor. Most of the directed upwards cough (towards the ceiling exhaust vent) was successfully exhausted. Based on these results it can be suggested that a good contaminant control solution in hospital rooms is to position the TV exhaust as close as possible to the polluting source: the sick coughing patient in this case. Similar arrangement has been suggested before as well (Cheong and Phua 2006, Noakes et al. 2009, Tung et al. 2009). The impact of the posture of the coughing patient on the background CO<sub>2</sub> concentration will be discussed in a following sub-section of this paper.

The doctor may not face only one of the patients, but as in the case when making visitations, he/she may stand by the bed to have view prospective of both patients (defined as "sideways" relative to the coughing patient, Figure 1c). This condition was studied at ventilation rate equal to 6 h<sup>-1</sup> only. In Figure 3 the excess CO<sub>2</sub> concentration at the mouth of the doctor when facing the coughing patient and when standing sideways are compared. It can be seen that there is relatively small change in the concentration measured at the mouth of the sideways standing doctor after the cough. The PCT also increased to nearly 10 s (more than doubled) after the cough was triggered when doctor was turned sideways. The PCL also drastically dropped from 10197 ppm to 194 ppm, over 50 times decrease in peak exposure. The reason is that being turned to face both patients, i.e. sideways, the doctor's body does not play the role of an obstacle for the coughed jet. Therefore the high momentum cough jet just sweeps by the doctor. However small portion from the patient's cough is entrained by the boundary layer around doctor's body and is brought to the mouth, after longer time, PCT = 9.7 s compared to the case when doctor is facing the coughing patient, PCT = 4.1 s.

### **Exposure of the second patient to coughed air**

The effect of cross-infection among patients was also studied. In this scenario the exposed patient was facing the coughing one. The case when the exposed patient was lying on back, i.e. facing the ceiling was not studied as preliminary measurements showed very low excess in the CO<sub>2</sub> concentration measured at the mouth of the exposed patient. In this case the second patient was simulated by the thermal manikin placed in the second bed (1.3 m (4.27 ft) away), with its head turned facing the coughing dummy's head. The doctor was not present in the room. The results of these measurements are shown in Figure 4. The increase of the ventilation rate to 12 h<sup>-1</sup> increased the room air movement and thus the mixing, i.e. the dilution of the coughed air. This resulted in lower CO<sub>2</sub> concentration at the breathing zone of the exposed patient; the concentration of CO<sub>2</sub> was reduced more than twice compared to the other two lower ventilation rates at all ventilation rates studied. The PCL for 3, 6 and 12 h<sup>-1</sup> was as follows: 5518, 5073 and 1786 ppm respectively. The PCT for 3 and 6 h<sup>-1</sup> was around 6 s (respectively 5.9 s and 6.1s), while for 12 h<sup>-1</sup> it was slightly higher – 8.4 s. The high initial velocity of the coughed CO<sub>2</sub> and the relatively low background velocities at 3 and 6 h<sup>-1</sup> (Bolashikov et al. 2010) kept the PCL at the mouth of the exposed patient quite high (Figure 4). This also resulted in the shorter PCT measured for the two lower ventilation rates. The exposure of the second patient to the coughed air was substantially lower than the exposure of the doctor when facing the coughing manikin (Figure 2a). The reasons can be that the exposed patient was located at longer distance from the coughing patient (1.3 m (4.27 ft)) than the doctor (0.55 m (1.8 ft)). The exposed patient was lying in the second bed at the same height from the floor as the coughing patient, which resulted in horizontal penetration of the coughed air. When the doctor was present in the room (Bolashikov et al. 2010) the coughed air first hit the abdominal area of the manikin's body decreasing its momentum, and then moved upwards towards the breathing zone. Hence, the level of exposure for the occupant (health care worker or additional patient/visitor) depends also on the positioning relative to the cough direction: lying or standing still, facing or turned sideways.

### **Spread of coughed air in the room**

Figure 5 shows the level of excess CO<sub>2</sub> concentration in the occupied zone at 1.7 m (5.58 ft) height close to the feet side of the bed with the coughing patient (point A, Figure 1a). When the doctor was beside the bed and close to the source of contamination (the sick patient) the highest excess CO<sub>2</sub> level in the occupied zone was observed at 6 h<sup>-1</sup> and the lowest at 3 h<sup>-1</sup> (Figure 6a). A plausible explanation can be the flow pattern in the room which depends on the amount of air supplied, the type of diffusers, their positioning, supply air temperature etc. and hence determines the level of mixing in the space (Bolashikov et al. 2010).

At all ventilation rates studied the background CO<sub>2</sub> concentration after the cough was slightly lower when the coughing patient was lying on the back and coughing upward compared to the case when the coughing patient was lying on one side (Figure 5b). A possible explanation can be that the body of the doctor deflected the coughed jet when the patient coughed sideways, and the background room velocities increased the mixing of the coughed air compared to the case when the coughing was upwards.

The background CO<sub>2</sub> concentration was result of the airflow interaction in the room which depended on the direction of the cough, i.e. the posture of the coughing patient, and the airflow pattern in the room, which was influenced by the ventilation rate.. The highest excess CO<sub>2</sub> concentration in the occupied zone (Point A, Figure 1a) was measured at 12 h<sup>-1</sup> when the coughing patient was lying on the back and coughing upward. The airflow interaction remains to be studied in the future.

In Figure 5c the excess CO<sub>2</sub> concentration in the occupied zone in point A (Figure 1a) at the three ventilation rates is compared in the case when only the two patients were present in the room (doctor was not in the room). In this case the excess CO<sub>2</sub> concentration also increased slightly after the cough.

The results in Figure 5b reveal that in general the decrease of the ventilation rate lead to increase of the PCT from 140 s at 12 h<sup>-1</sup> coughing upwards to 590 s at 3 h<sup>-1</sup> and coughing upwards. The comparison of the results also revealed that the posture of the coughing patient and the presence or absence of the doctor in the room had an impact on the PCT. The impact of these factors on the PCL was even stronger. For example when the doctor was facing the infected patient coughing sideways the PCL was highest at 6 h<sup>-1</sup> and when the infected patient was coughing upward the PCL was highest at 12 h<sup>-1</sup>. As already discussed the complex airflow interaction in the room has affected the diffusion of the coughed air. In general the results of the excess CO<sub>2</sub> measurements reveal that due to the interaction of the coughed flow with the background flow the CO<sub>2</sub> concentration in the room will rise and will result in exposure risk, though substantially less than compared to the direct exposure of the doctor and the second patient.

The position of the doctor, sideways or facing the coughing patient showed influence on the spread of the coughed air as well. The excess CO<sub>2</sub> concentration in Point A within the occupied zone was higher when the doctor was facing the coughing patient than when the doctor was turned sideways (Figure 6). In the later case most of the coughed flow passed by without being deflected by the body and this resulted in the lower concentration in the background in proximity close to the feet of the coughing patient.

The results of the present study show that the increase of the CO<sub>2</sub> concentration in the background after the cough was relatively small but still indicating for possible risk from airborne cross-infection. The results reveal



that beside the background ventilation rate the exposure in the room was affected by other factors, namely the posture of the coughing patient, the posture of the doctor, etc. In the future it is recommended to study the exposure in the case doctor seated at the bed of the coughing patient, lay out of the beds in the room, positioning of the supply and exhaust diffusers, etc.

## CONCLUSIONS

Based on the results of this study, the following conclusions can be drawn:

- The recommended in the present standards and guidelines air change rate of  $12\text{ h}^{-1}$  in hospital isolation rooms with mixing ventilation does not reduce the risk of airborne cross-infection for a distance close to a coughing sick person. Advanced, more efficient air distribution methods need to be developed in order to control the spread of the pollutants generated by the sick person;
- The posture of the coughing infected patient, lying on side or on back, had great impact on the exposure of the doctor and the second patient: maximal exposure occurred when the doctor and the second patient were facing the coughing patient lying sideways; the maximum PCL of 10228 ppm was measured at  $3\text{ h}^{-1}$ . Under these conditions the simulated cough increased dramatically the exposure even when the ventilation rate was increased up to  $12\text{ h}^{-1}$  and was at maximum 6847 ppm. The increase in the ventilation rate from  $3\text{ h}^{-1}$  to  $12\text{ h}^{-1}$  decreased the PCL from 10228 to 6847 ppm and the time for the  $\text{CO}_2$  concentration at the breathing zone to return back to the background  $\text{CO}_2$  concentration level before the cough, but had little impact on the PCT (approximately 4 s for all three tested ventilation rates). The risk of direct exposure to coughed air was minimal when the coughing patient was lying on his/her back; PCL was within always below 200 ppm. In this case also the risk from contamination via inhalation or ingestion of large particulate matter is smallest;
- The exposure of the doctor standing near the bed of the coughing patient and turned sideways was nearly 50 times lower than when the doctor was facing the patient and had similar exposure level as in the case when the sick patient was coughing upwards towards the ceiling;
- The excess  $\text{CO}_2$  concentration measured in the occupied zone near the bed of the coughing patient increased after the cough was generated, suggesting possible increased risk for airborne cross-infection for the staff and visitors in the room;
- It is recommended to study the exposure in the case when doctor seated at the bed of the coughing patient, when moving between the beds, different lay out of the beds in the room, positioning of the supply and exhaust diffusers, etc.

## ACKNOWLEDGEMENTS

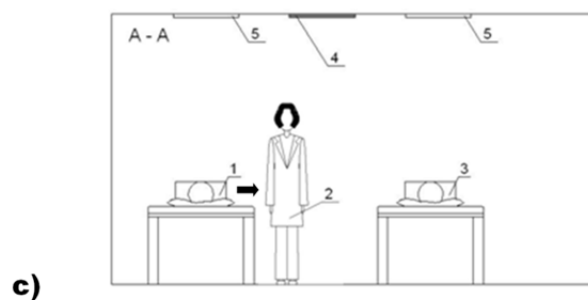
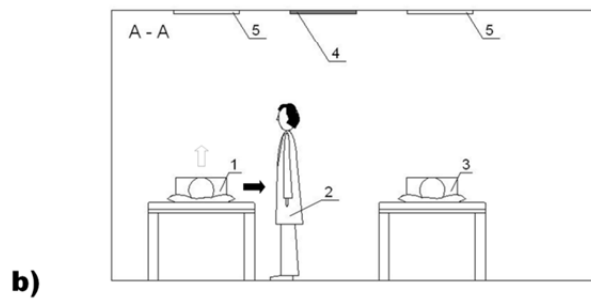
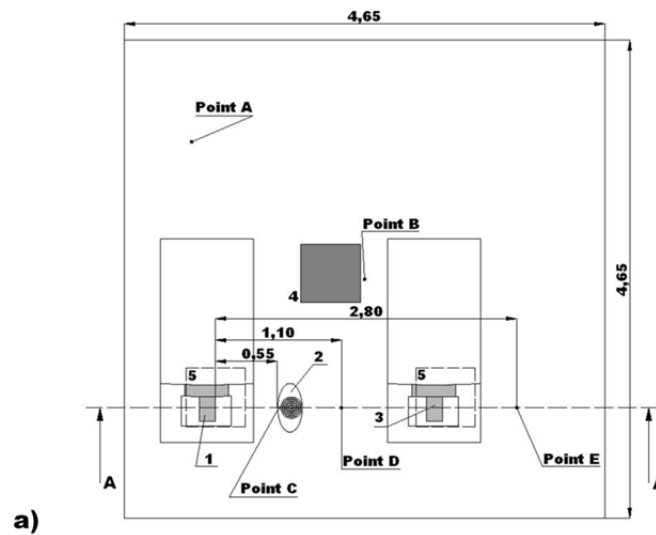
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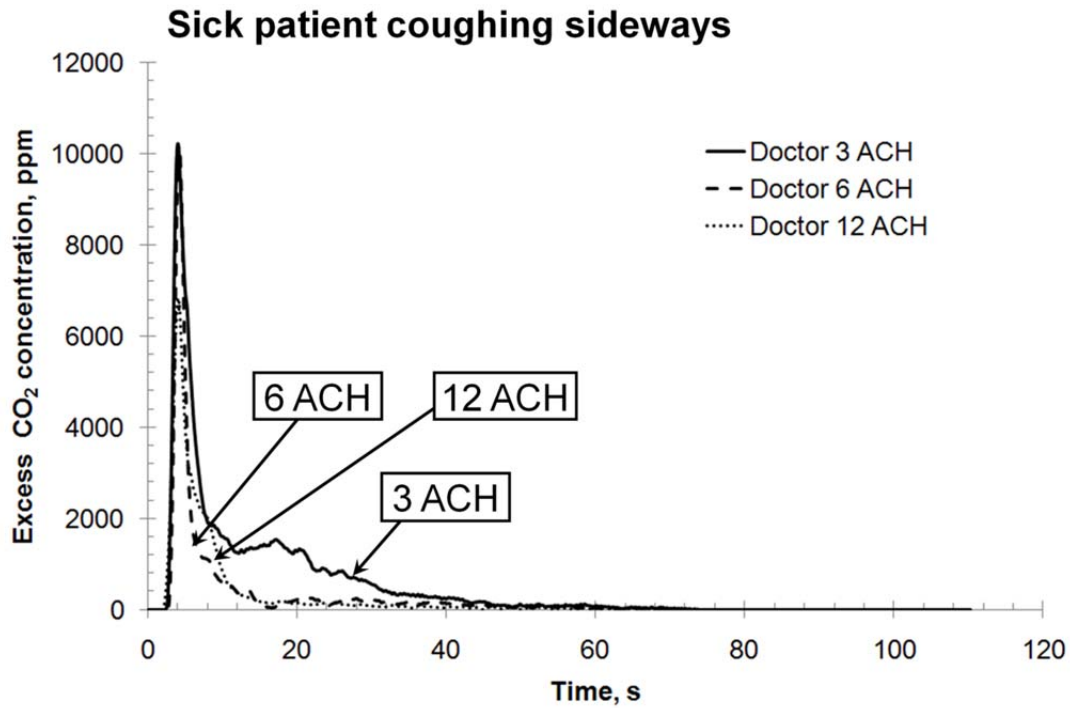
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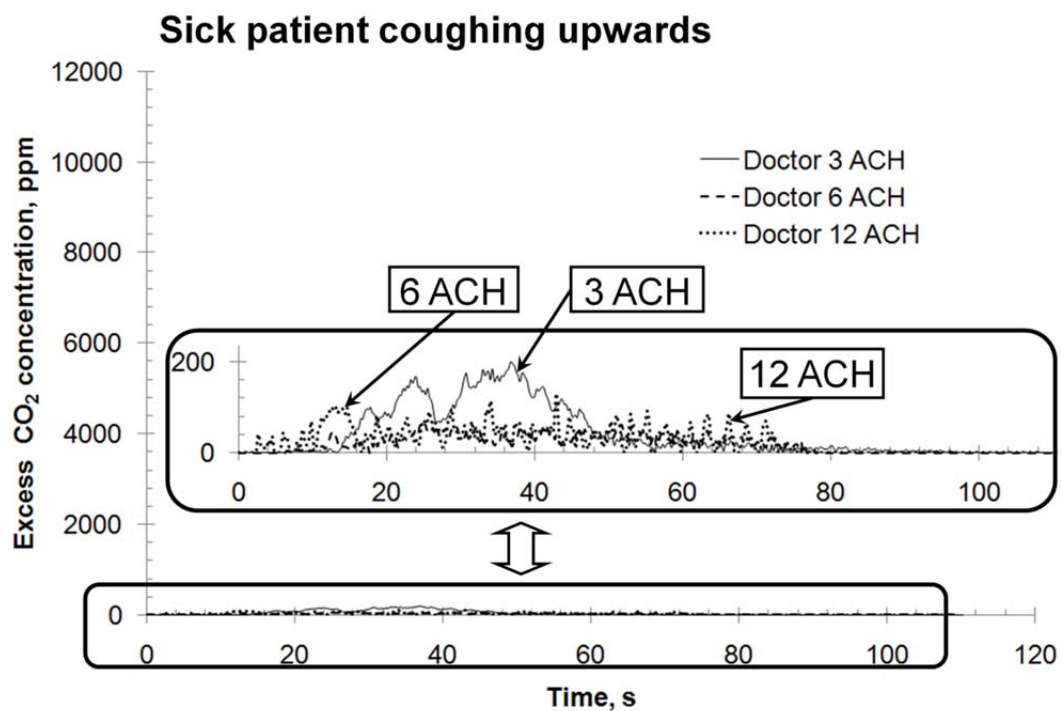
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**Figure 1. Sketch of the set-up in the full-scale room: a) top view, b) side view doctor facing patient and c) side view doctor turned sideways to cough flow - coughing patient lying on one side and was facing the doctor, c) coughing patient lying on back and facing the ceiling: 1 – coughing “patient” lying in bed, 2 – standing “doctor” facing the coughing manikin, 3 – exposed patient lying in bed, 4 – 4-way air supply diffuser, 5 – exhaust diffusers. The arrows on Figure 1b and 1c show the direction of the generated cough.**

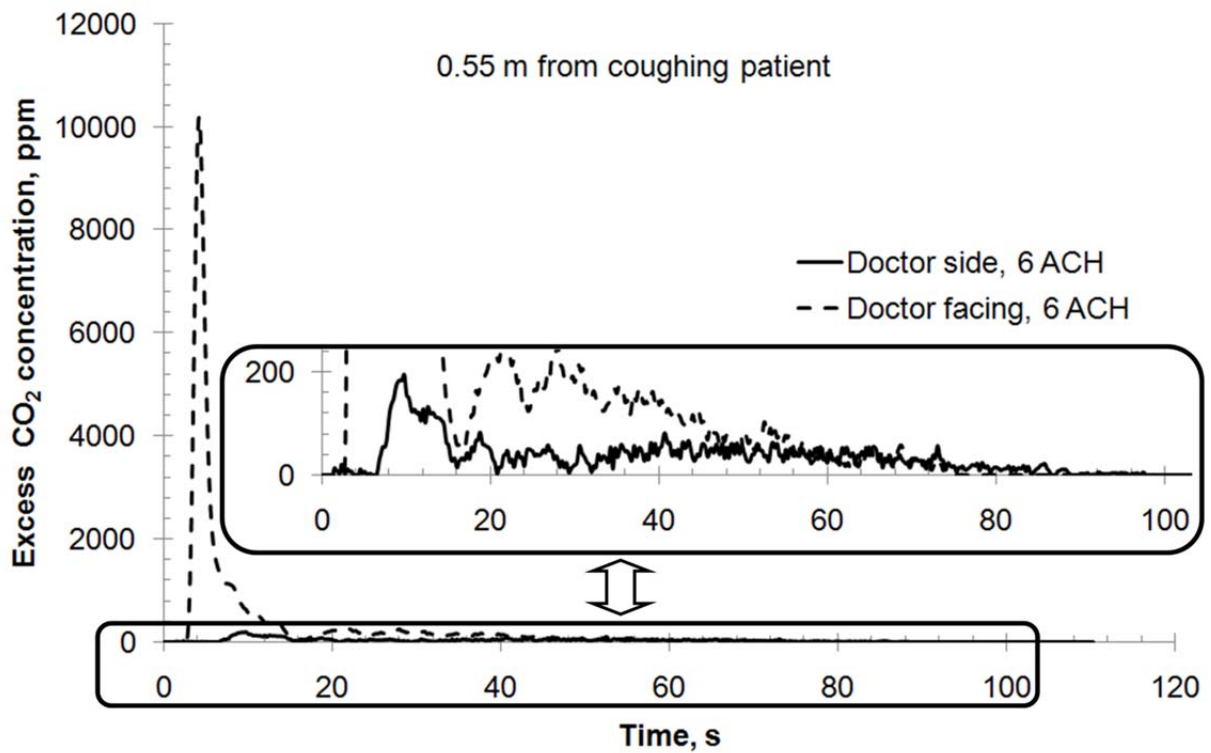


**a)**

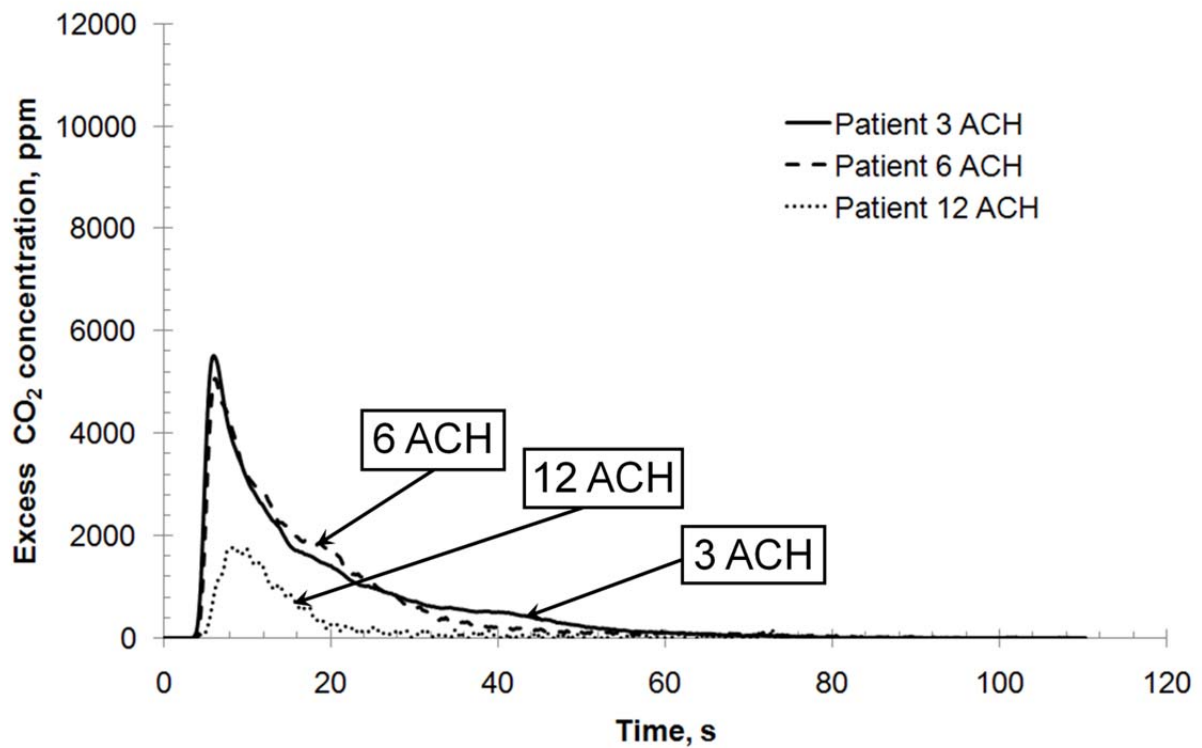


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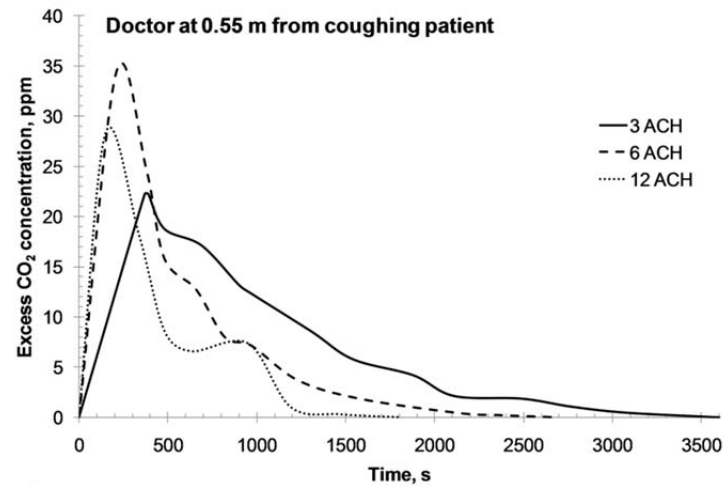
**Figure 2.** CO<sub>2</sub> excess concentration change in time at the mouth of the “doctor” standing 0.55 m (1.8 ft) in front of the “coughing patient” when the latter is a) lying on one side; b) lying on the back in a bed in a hospital mock-up room ventilated at air change of 3, 6 and 12 h<sup>-1</sup>.



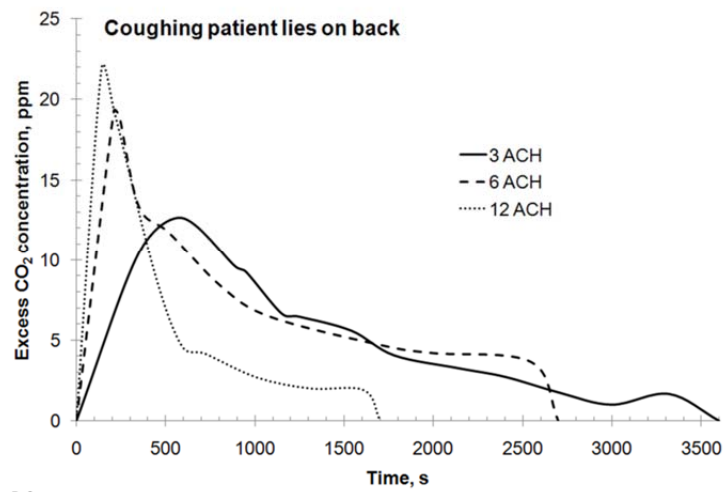
**Figure 3.** Excess CO<sub>2</sub> concentration change in time at the mouth of the “doctor” when standing sideways at 0.55m (1.8 ft) and viewing the two patients (Figure 1c) and when facing the coughing patient at 0.55m (1.8 ft) (Figure 1b) . The coughing patient is lying on one side and coughing sideways.



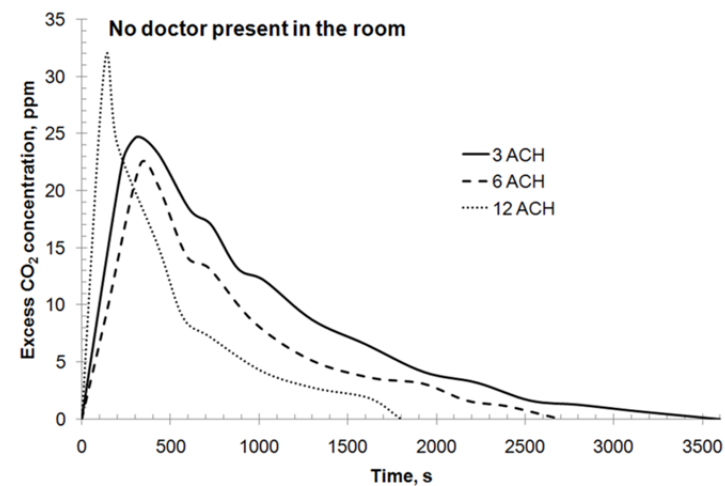
**Figure 4.** CO<sub>2</sub> concentration change in time at the mouth of the “exposed patient” lying in the second bed and facing the coughing patient lying on one side. Results obtained at three different air - 3, 6 and 12 h<sup>-1</sup> are compared.



a)



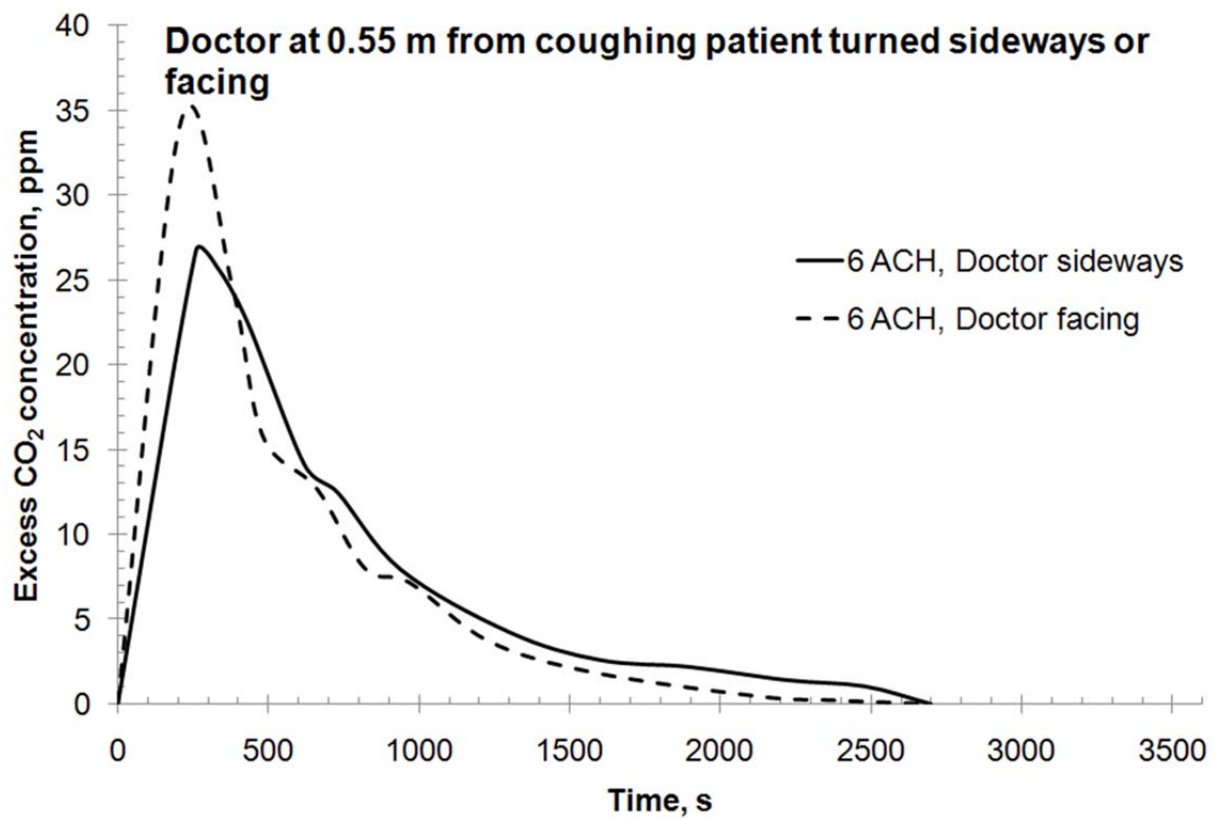
b)



c)

**Figure 5. CO<sub>2</sub> concentration change in time at 1.7 m (5.58 ft) above the floor in the occupied zone near the feet of the coughing patient: a) doctor is facing the coughing patient lying on its side; b) doctor is facing the coughing patient lying on its back; c) the coughing and the exposed patients lying on their side and facing each other. Results obtained at three different air changes - 3, 6 and 12 h<sup>-1</sup> are compared.**





**Figure 6. Excess CO<sub>2</sub> concentration change in time at 1.7 m (5.58 ft) above the floor in the occupied zone near the feet of the coughing patient (Point A, Figure 1a) when the doctor is facing (Figure 1b) or turned sideways (Figure 1c) relative to the coughing patient. Results obtained at 6 h<sup>-1</sup>.**